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Advances in Space Research 36 (2005) 1444–1447
ADVANCES IN SPACE RESEARCH (a COSPAR publication)
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Multi-point observation of the high-speed flows in the plasma sheet

R. Nakamura [a,*], W. Baumjohann [a], C. Mouikis [b], L.M. Kistler [b], A. Runov [a], M. Volwerk [a,1], Y. Asano [a], Z. Vörös [a], T.L. Zhang [a], B. Klecker [c], A. Balogh [d], H. Reme [e]

[a] *Space Research Institute, Austrian Academy of Sciences, 8042 Graz, Austria*
[b] *U. New Hampshire, Space Science Center, Durham NH 03824, USA*
[c] *MPE, Postfach 1312, 85741 Garching, Germany*
[d] *Imperial College, Prince Consort Road, London SW7 2BZ, UK*
[e] *CESR/CNRS, 9 Avenue du Colonel Roche Toulouse F-31028, France*

Received 28 October 2004; received in revised form 5 April 2005; accepted 27 May 2005

Abstract

The structure of the high-speed flows in the midtail plasma sheet is discussed based on results from multi-point observation of Cluster spacecraft in summer 2001 and 2002. The average rate of change in flow speed along the "dawn–dusk" direction (perpendicular to the main flow and in the plane of the tail current sheet) and along the "north–south" direction suggests that the full width of the flow channel is 12,000–17,000 km in the "dawn–dusk" direction and about 9000–12,000 km in the "north–south" direction. This is consistent with the results obtained from the analysis of the dipolarization front of the flows. The profile of the gradient of the flow in the north–south direction and the shape of the dipolarization front suggest that the BBF has the shape of a localized flux tube.

Keywords: Bursty bulk flow; Plasma sheet; Cluster

1. Introduction

Transient fast plasma flows, called bursty bulk flows (BBF), play a key role in the Earth's magnetotail (Baumjohann et al., 1990; Angelopoulos et al., 1992).

Most likely, these fast flows are due to acceleration in the reconnection region. It is crucial to quantify the BBF signatures to understand the magnetic fluxtransport process or to discuss the energy budget problems in the magnetosphere. Many studies using quite different methods with single spacecraft have come to the conclusion that a BBF is expected to be limited in dawn–dusk extent with a spatial scale of 3–5R_{E} (Angelopoulos et al., 1997; Kauristie et al., 2000; Nakamura et al., 2001). These results were obtained by comparison between satellite and ground-based data, and low-altitude observations of convection, equivalent current, and auroral pattern. In situ multi-point observations provide more direct evidence on the spatial scale. From two-spacecraft observations Sergeev et al. (1996) inferred a scale size of 1–3R_{E}.

In this paper, we highlight several Cluster studies as well as new results on the fast flows that used multipoint data analysis using data from 2001 and 2002, when the tetrahedron scale was 2000 and 4000 km, respectively. We discuss mainly two topics: spatial scale and shape of the BBFs. Cluster data shown in the paper are obtained by the the fluxgate magnetometer (FGM) experiment (Balogh et al., 2001) and by the Composition and Distribution Function Analyser (CODIF) and the

* Corresponding author.
E-mail address: rumi.nakamura@oeaw.ac.at (R. Nakamura).
[1] Also at: MPE, Postfach 1312, 85741 Garching, Germany.

0273-1177/$30
doi:10.1016/j.asr.2005.05.101

Hot Ion Analyser (HIA) of the ClusterIon Spectrometry (CIS) experiment (Réme et al., 2001).

2. Spatial scale of the flow

Using proton flow data from the Cluster 1, 3 and 4 spacecraft (which have identical CIS/CODIF plasma instruments) the gradient scale of the Earthward bursty bulk flow was obtained by Nakamura et al. (2004). Data from the 2001 tail period were used when at least one of the spacecraft observed a BBF. BBFs were selected using the following condition: plasma $\beta_{XY} > 2$, and $V_{\perp XY} > 300$ km/s, where $V_{\perp XY}$ is the equatorial component of the flow perpendicular to the magnetic field. Due to Cluster's apogee at $19R_E$ and the condition in X and in plasma β, the location of the events is restricted to the night-side equatorial region, i.e., $-19 < X < -15R_E$, $|Y| < 11R_E$ and $-4 < Z < 6R_E$.

The spatial gradients of high-speed flows were estimated using a combination of two-point observations from the Cluster spacecraft along the "dawn–dusk" direction (perpendicular to the main flow and in the plane of the tail current sheet), the Y_{mod} direction, and along the north–south direction (perpendicular to the tail current sheet), the Z direction. The events were selected only when both spacecraft were in the plasma sheet ($\beta_{XY} > 0.5$), and at least one of them fulfilled the condition of the BBF given before. When determining the north–south gradient those events were excluded when the current sheet configuration was not in a normal orientation, i.e., $\Delta B_X/\Delta z < 0$, although such cases were seldom (about 10%). The horizontal component of the flow velocity, V_{XY}, was used to calculate the difference in the flow speed, ΔV. The result is shown in the histograms in Fig. 1. Shown are the occurrence of the rate of change in the flow speed in (a) Y_{mod}, the modified dawn–dusk direction, and (b) along the north–south axis. The event numbers are larger for the north–south pairs (Fig. 1(b)) due to the fact that only three spacecraft have ion measurements and due to the orbital condition of Cluster. The average (thick bar) or median (thin bar) of the spatial gradients in the figure indicates that the full width of the flow channel is 2–$3R_E$ in the "dawn–dusk" direction assuming that the flow channel has a triangular-shape cross-section. This is a value comparable to the previous estimates. The velocity gradient at the duskward edge of a flow (dashed line) tends to be sharper than that at the dawnward edge (solid line), possibly reflecting an asymmetry in the magnetosphere–ionosphere coupling process associated with the flow. The full width of the flow channel is 1.5–$2R_E$ in the north–south direction. More details of this statistical analysis are given in Nakamura et al. (2004).

3. Shape of the flow channel

Structure of the flows in the north–south direction is further determined by examining the relationship between the gradient in flow and the magnetic field orientation. The interest here is to examine how the flows are distributed relative to the equator. This can be checked from the rate of the change in flow along the Z direction, $\Delta V/\Delta z$. For northern hemisphere, for example, this number is negative if the flow peak is at the equatorial side, and is positive if the flow peak is at the off-equatorial side. In the southern hemisphere this relationship will be opposite. We use the same data set shown in Fig. 1(b), except for selecting cases when both spacecraft are in the same hemisphere. This selection reduces the total number of the data to 713, which is still large enough for the statistics. Since the selected events are only during nominal current sheet orientation ($\Delta B_X/\Delta z > 0$), we use B_X to infer relative location from the equator and $\alpha = \Delta V/\Delta z \times \mathrm{sign}(B_X)$ to examine whether the flow was

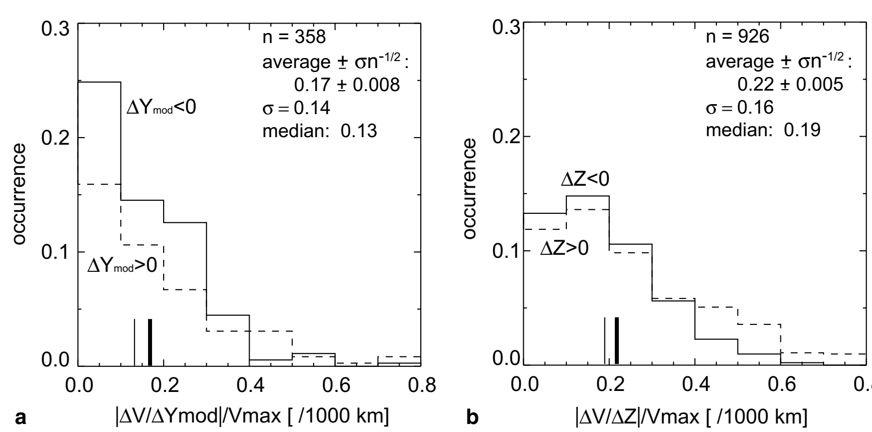

Fig. 1. Histograms showing the occurrence of the rate of change in flow speed in (a) Y_{mod}, the modified dawn–dusk direction, and (b) along the north–south axis. The occurrence numbers are normalized by the total number of the events given at the top of the panel. The rates are normalized for a distance of 1000 km. The dashed line represents cases when the flow speed is decreasing in the duskward or northward direction, whereas the solid line represents cases when the flow speed is decreasing in the dawnward or southward direction (adapted from Nakamura et al., 2004).

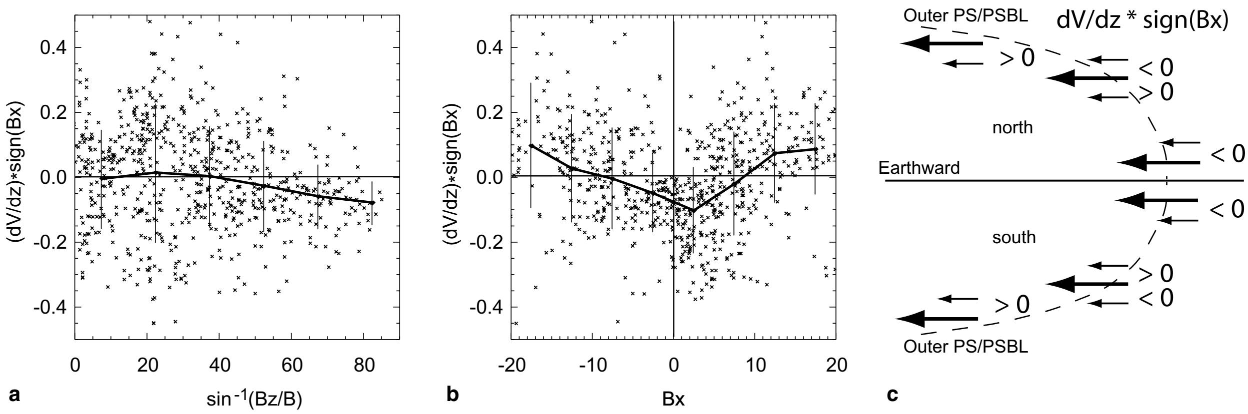

Fig. 2. Relationship between $\Delta V/\Delta z \times \mathrm{sign}(B_X)$ to (a) the latitude angle and to (b) BX. (c) Profile of the horizontal component of the flow in the X–Z plane.

larger at the equator side ($\alpha < 0$) or at the off-equator side ($\alpha > 0$). Here, we again use X and Y component to calculate the gradient of the total flow speed, V, same as Fig. 1. Fig. 2 shows the relationship between the α and (a) the latitude angle (inclination) of the field, $\sin^{-1}(B_Z/B)$, and (b) B_X. The solid line shows the average profile and the vertical bars indicate 2σ (standard deviations). It can be seen that the negative α points become more significant for large latitude angle or small $|B_X|$ value, i.e., close to the equator. Both positive and negative α values are apparent as the latitude angle decreases and $|B_X|$ increases, corresponding to off-equatorial region. Mainly positive α values are seen at large $|B_X|$ region, which corresponds to BBF events in the vicinity of the outer edge of the plasma sheet where only positive α cases fulfill our data selection criterion, i.e., both spacecraft in the plasma sheet. These relationships of the gradients relative to the equator are illustrated in Fig. 2(c). The Earthward fast flows consist of flow peaks both in the equator and away from the equator. Note that the fast flows selected here took place in the central plasma sheet and are not the plasma sheet boundary layer ion beams. The most likely shape of the flowing plasma will then be as illustrated in Fig. 3. That is, a localized flow channel in the X–Y plane and a shape similar to a localized flux-tube in X–Z plane. Such distribution of the flows is consistent with the model of the BBF by Birn et al. (2004), in which the bubble is modelled as a localized flux tube moving Earthward. A Geotail statistical study also showed a simultaneous development of the fast flow both near the equator and away from the equator after substorm onset, although for tailward flows (see Fig. 14 from Nagai and Machida, 1998).

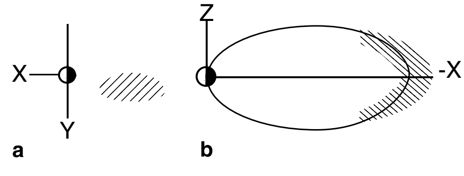

Fig. 3. Schematic shape of the BBF in (a) the X–Y plane and in the (b) X–Z plane based on the statistical studies of the multi-point flow observation and the shape of the dipolarization front.

Another way of determining the spatial structure of a bursty bulk flow is to examine the characteristics of the dipolarization front. Sergeev et al. (1996) introduced an analysis of the magnetic field disturbances to characterize the high-speed moving plasma based on the plasma bubble model (Chen and Wolf, 1993). Sergeev et al. (1996) showed that Earthward moving plasma structures, such as the bubbles, are separated from the plasma ahead of them by a discontinuity. This corresponds to a front layer identified from the change in B_Z and called the dipolarization front. The orientation of the discontinuity can be determined by the minimum variance of the magnetic field of the dipolarization. From the shape of this front the scale size of the bubble can be inferred. Using ISEE 1, 2 measurements, Sergeev et al. (1996) estimated the dawn–dusk scale size of the bubble to be 1–3R_E.

The orientation of the dipolarization front is also investigated based on Cluster observations of two isolated bubble-type bursty bulk flow events on July 22, 2001 (Nakamura et al., 2002) and on September 1, 2002 (Nakamura et al., 2005). Using the four spacecraft measurement, the orientation of the dipolarization front and its movement were determined. For the first event the spacecraft along the boundary was less than 1500 km and the dipolarization front was identified as a planar structure. On the other hand, Cluster could identify edge effects for the second event, when the tetrahedron scale was about 4000 km. It was inferred from the change of orientation of the dipolarization front to be 1.5–2.2R_E in dawn–dusk direction. In both cases, the dipolarization was propagating toward Earth and toward the equator and the dipolarization front is oriented so that it forms a concave shape in the X–Z plane and convex shape in the X–Y plane. This shape of the dipolarization front again is consistent with the shape shown in Fig. 3.

4. Conclusion

Cluster observations enabled us to identify several important characteristics of the fast flows using multipoint data analysis techniques. Based on statistical studies of the spatial gradient of the flows and event studies analyzing the dipolarization front, the structure of plasma sheet fast flows was determined. In the dawn-to-dusk direction, the flow channel has a spatial scale of 2–3R_{E} and with a sharper gradient on the duskward side. In the north–south direction, flow channel has a spatial scale of about 1.5–2R_E and consists of flows both centered at the equator and off-equator. These results suggest that the bursty bulk flow has a shape similar to that of a localized flux tube.

Acknowledgments

We thank T. Nagai and V.A. Sergeev for helpful discussions, H. Eichelberger and G. Laky for helping in data processing. The work at IWF was partly supported by INTAS 03-51-3738 Grant.

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